STUDY OF $\mathrm{K_{e4}}$ DECAYS IN THE NA48/2 EXPERIMENT AT CERN

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Large samples of kaon decays have been collected in $2003-2004$ by the NA48/2 collaboration in the charged ($\mathrm{K}^{\pm} \to \pi^+\pi^-\mathrm{e}^{\pm}\nu$) and neutral ($\mathrm{K}^{\pm} \to \pi^0\pi^0\mathrm{e}^{\pm}\nu$) $\mathrm{K_{e4}}$ modes. In the charged mode, form factors have been extensively studied from a sample of more than one million decays and a preliminary branching ratio measurement is reported here. In the neutral mode, a sample of 44 000 decays has been analyzed and provides a new branching ratio value with $1-2\%$ precision, a factor of ten improvement with respect to the current knowledge. Both modes contribute to the study of low energy QCD and are powerful tests of Chiral Perturbation Theory predictions.

1 Introduction

Kaon decays have been identified as a perfect laboratory to study low energy strong interaction. Semileptonic four-body decays are of particular interest because of the small number of hadrons in the final state which are related to the study of $\pi\pi$ interaction. The development of chiral perturbation theory (ChPT)[1] over more than 30 years has reached a competitive precision level in its predictions of both $\pi\pi$ scattering lengths values and form factors appearing in the weak hadronic current of the $\mathrm{K_{e4}}$ decay matrix element. The global analysis of $\pi\pi, \pi K$ and $\mathrm{K_{e4}}$ data allows the determination of the Low Energy Constants (LEC) of ChPT at Leading and Next to Leading Orders (LO,NLO,NNLO)[2,3] and subsequent predictions of form factors and decay rates. Current experimental measurements[4] and NA48/2 improved sensitivity are shown in Table 1. The possibility to study high statistics samples collected concurrently by NA48/2 in several modes will bring improved inputs and will allow stronger tests of ChPT predictions.

Table 1: Number of analyzed $\mathrm{K_{e4}}$ events, measured decay rates and NA48/2 improvements for the two reported modes. Relative errors are given within parentheses.

Decay mode	PDG 2010		This measurement	
$\mathrm{K}^+ \to \pi^+\pi^-\mathrm{e}^+\nu_e$	418 000	3304 ± 81 (2.4%)	1.11 10^6	28 (0.8%)
$\mathrm{K}^+ \to \pi^0\pi^0\mathrm{e}^+\nu_e$	37	1777 ± 323 (18.2%)	44 000	34 (1.6%)

2 Kinematics

The $\mathrm{K_{e4}}$ decay is fully described by the five kinematic Cabibbo-Maksymowicz variables[7]: two invariant masses $S_\pi = M^2_{\pi\pi}$ and $S_e = M^2_{e\nu}$ and three angles θ_π, θ_e and ϕ. Form factors can be developed in a partial wave expansion[8]. Limiting the expansion to S- and P- wave and considering a unique phase δ_p for all P-wave form factors, two complex axial (F,G) and one complex vector (H) form factors contribute to the transition amplitude: $F = F_s\ e^{i\delta_s} + F_p\ e^{i\delta_p} cos\theta_\pi$, $G = G_p\ e^{i\delta_p}$, $H = H_p\ e^{i\delta_p}$. Four real form factors (F_s, F_p, G_p and H_p) and a single phase ($\delta = \delta_s - \delta_p$) have to be measured, including their energy variation. In the neutral mode, the variables θ_π and ϕ are irrelevant and the form factors reduce to the single F_s value due to Bose statistics. In addition if $\Delta I = \frac{1}{2}$ holds, F_s values should be equal in the charged and neutral $\mathrm{K_{e4}}$ modes.

3 Experimental setup

Two simultaneous $\mathrm{K}^\pm$ beams were produced by 400 GeV protons from the CERN/SPS impinging on a beryllium target. Opposite charge particles with a central momentum of 60 GeV/c and a momentum band of $\pm 3.8\%$ were selected and focused $\sim$ 200 m downstream at the first spectrometer chamber. A schematic view of the beam line can be found in [5] and a detailed description of the NA48/2 detector in [6]. The magnetic spectrometer consists of a dipole magnet surrounded by two sets of drift chambers (DCH). The momentum of charged decay products is measured with a relative precision of $\sim$ 1% for 10 GeV/c tracks. It is followed by a scintillator hodoscope consisting of two planes segmented into horizontal and vertical strips achieving a very good $\sim$ 150 ps time resolution. A liquid krypton calorimeter (LKr), 27 radiation length thick, is used to measure electromagnetic deposits and identify electrons through their E/p ratio (the energy and position resolutions are $\sim$ 1% and $\sim$ 1.5 mm (resp.) for 10 GeV showers). A two-level trigger logic selects and flags event with a high efficiency for both $\mathrm{K_{e4}}$ topologies.

4 Branching ratio measurements

The $\mathrm{K_{e4}}$ branching ratio (BR) is measured relative to a normalization mode (n) as :

$$\mathrm{BR(K_{e4})} = \frac{N_s - N_b}{N_n} \cdot \frac{A_n\ \varepsilon_n}{A_s\ \varepsilon_s} \cdot \mathrm{BR}(n) \tag{1}$$

where N_s, N_b, N_n are the numbers of signal, background and normalization candidates, A_s and ε_s are the geometrical acceptance and trigger efficiency for the signal sample, A_n and ε_n the geometrical acceptance and trigger efficiency for the normalization sample.

4.1 The charged ($\mathrm{K}^\pm \to \pi^+\pi^-\mathrm{e}^\pm\nu$) $\mathrm{K_{e4}}$ analysis

The charged $\mathrm{K_{e4}}$ BR is measured relative to the abundant $\mathrm{K}^\pm \to \pi^+\pi^-\pi^\pm$ mode ($\mathrm{BR}(n) = (5.59 \pm 0.04)\%$) which has a similar topology in terms of number of charged particles and is recorded concurrently by the same trigger logic. A very large sample of 1.13 million charged $\mathrm{K_{e4}}$ decays has been analyzed [5] to measure $\pi\pi$ scattering lengths with a few percent precision. Form factors values, and their energy dependence, have been obtained relative to a single overall factor f_s which can be determined from the BR value. The energy dependence is described using a series expansion of the dimensionless invariants $q^2 = (S_\pi/4m^2_{\pi^+}) - 1$ and $S_e/4m^2_{\pi^+}$ (three terms for F_s, two terms for G_p and one term for F_p, H_p). It is recalled below:

$$\begin{array}{llllllll}
f'_s/f_s = & 0.152 & \pm 0.007_{\rm stat} & \pm 0.005_{\rm syst} & g_p/f_s = & 0.868 & \pm 0.010_{\rm stat} & \pm 0.010_{\rm syst} \\
f''_s/f_s = & -0.073 & \pm 0.007_{\rm stat} & \pm 0.006_{\rm syst} & g'_p/f_s = & 0.089 & \pm 0.017_{\rm stat} & \pm 0.013_{\rm syst} \\
f'_e/f_s = & 0.068 & \pm 0.006_{\rm stat} & \pm 0.007_{\rm syst} & & & & \\
f_p/f_s = & -0.048 & \pm 0.003_{\rm stat} & \pm 0.004_{\rm syst} & h_p/f_s = & -0.398 & \pm 0.015_{\rm stat} & \pm 0.008_{\rm syst}
\end{array}$$

In the BR measurement, several requirements were loosened or removed from the event selection of the form factor analysis. Extra accidental track activity and possible accompanying photons were accepted while particle identification requirements were loosened. Many stability checks were performed ensuring the robustness of the procedure and defining systematic uncertainties. Out of $\sim 2.3\ 10^{10}$ total recorded triggers, $1.11\ 10^{6}$ K_{e4} candidates were selected, 10545 background events and $1.9\ 10^{9}$ normalization candidates. The geometrical acceptances (based on a GEANT3 simulation) have large and similar values of 18.22%(K_{e4}) and 24.18%($K_{3\pi}$). They make use of our best knowledge of the signal and normalization matrix elements [5,9]. Trigger efficiencies are measured using minimum bias control triggers [a]. They have high similar values of 98.3%(K_{e4}) and 97.5%($K_{3\pi}$). The analysis has been performed for each kaon charge (K^{-}_{e4} mode has never been measured) and the results statistically combined. The details of the common systematic uncertainties are given in Table 2. The preliminary values (including radiative K_{e4} decays) are found to be:

$$\mathrm{BR}(K^{+}_{e4}) = (4.277 \pm 0.009_{stat+trig})10^{-5} \text{ and } \mathrm{BR}(K^{-}_{e4}) = (4.283 \pm 0.012_{stat+trig})10^{-5} \quad (2)$$

$$\text{combined into } \mathrm{BR}(K_{e4}) = (4.279 \pm 0.006_{stat+trig} \pm 0.015_{\mathrm{syst}} \pm 0.031_{ext})10^{-5} \quad (3)$$

The total error $\pm 0.035\ 10^{-5}$ (0.8% relative) is dominated by the external error (0.7% relative). This measurement brings a factor of three improvement with respect to the world average [4] $(4.09 \pm 0.10)10^{-5}$ and a factor of more than five on the relative decay rate to $K_{3\pi}$: $\Gamma(K_{e4})/\Gamma(K_{3\pi}) = (7.654 \pm 0.030_{exp})10^{-4}$ while the world average is $(7.31 \pm 0.16)10^{-4}$.

Table 2: Summary of the uncertainties δBR $\times 10^{5}$ on BR(K_{e4}) measurements.

$K^{\pm} \to \pi^{+}\pi^{-}e^{\pm}\nu$		$K^{\pm} \to \pi^{0}\pi^{0}e^{\pm}\nu$	
Acceptance and beam geometry	0.0077	Beam geometry	0.0026
Muon vetoing	0.0068	Simulation statistic	0.0031
Accidental activity	0.0064	Form factor dependence	0.0052
Background control	0.0060	Background control	0.0091
Particle identification	0.0038	Electron identification	0.0026
Radiative effects	0.0034	Radiative effects	0.0060
Trigger efficiency	0.0051	Trigger efficiency	0.0208
Statistical error	0.0038	Statistical error	0.0120
External error	0.0308	External error	0.0324
Total	0.0346	Total	0.0424

4.2 The neutral ($K^{\pm} \to \pi^{0}\pi^{0}e^{\pm}\nu$) K_{e4} analysis

The neutral K_{e4} BR is measured relative to the more abundant mode $K^{\pm} \to \pi^{0}\pi^{0}\pi^{\pm}$ (BR(n) = (1.761±0.022)%). Both modes have a similar topology in term of final state: one charged particle and two π^{0} detected as four decay photons in the LKr. They are recorded concurrently by the same trigger logic. The event selection and reconstruction follow very closely those developed for the detailed analysis of the normalization mode [10]. Normalization events are required to cluster at low transverse momentum relative to the beam line (p_t) and reconstruct the $\pi\pi^{0}\pi^{0}$ mass close to the kaon mass when $m_{\pi^{+}}$ is assigned to the charged particle while signal events are required to reconstruct the $\pi\pi^{0}\pi^{0}$ mass away from the kaon mass together with a sizable p_t with respect to the beam line (Figure 1a). Additional requirements on the LKr energy associated to the charged track (E/p close to 1 and shower properties) ensure electron identification. The dominant background comes from $K_{3\pi}$ events with misidentification of the charged pion as an electron. Its contribution can be measured from control regions in the two modes. The background from $K_{3\pi}$

[a] because of downscaling, control samples have limited statistics

events with a subsequent $\pi^\pm \to e^\pm \nu$ decay has been studied from simulation and contributes one order of magnitude lower. The total background is estimated to be $\sim 1.3\%$ relative to the signal. Geometrical acceptances have been computed using GEANT3-based simulations, including our best knowledge of the normalization mode[11] which describes accurately the observed cusp effect and using the charged $\mathrm{K_{e4}}$ measured F_s value[5] for the signal simulation. They amount to 4.11% and 1.77% (resp.)[b]. The analysis selected $\sim 71\ 10^6$ normalization events, 44909 $\mathrm{K_{e4}}$ candidates and 598 background events. Trigger efficiencies have been measured from minimum bias control triggers. They vary with data taking conditions between 92 and 98% but the ratio $\varepsilon_n/\varepsilon_s$ is stable and close to unity. Preliminary systematic uncertainties have been quoted conservatively and are displayed in Table 2. Trigger efficiency related uncertainties will be reduced by a statistical treatment of sub-samples recorded in stable trigger conditions. A preliminary branching ratio value (including radiative $\mathrm{K_{e4}}$ decays) for the combined $\mathrm{K^\pm}$ mode is obtained as:

$$\mathrm{BR(K_{e4})} = (2.595 \pm 0.012_{\mathrm{stat}} \pm 0.024_{\mathrm{syst}} \pm 0.032_{ext})10^{-5} \qquad (4)$$

The total error $\pm 0.042\ 10^{-5}$ (1.6% relative) is dominated by the external error (1.25% relative). This measurement brings a factor of ten improvement on the total error with respect to the world average $(2.2 \pm 0.4)10^{-5}$. The agreement between data and simulation over the whole range of the $M^2_{\pi^0\pi^0}$ variable is shown in Figure 1b. The final form factor analysis will include a correction for small negative interference of the charged $\mathrm{K_{e4}}$ mode with final state charge exchange scattering $(\pi^+\pi^- \to \pi^0\pi^0)$ below $(2m_{\pi^+})^2$ threshold.

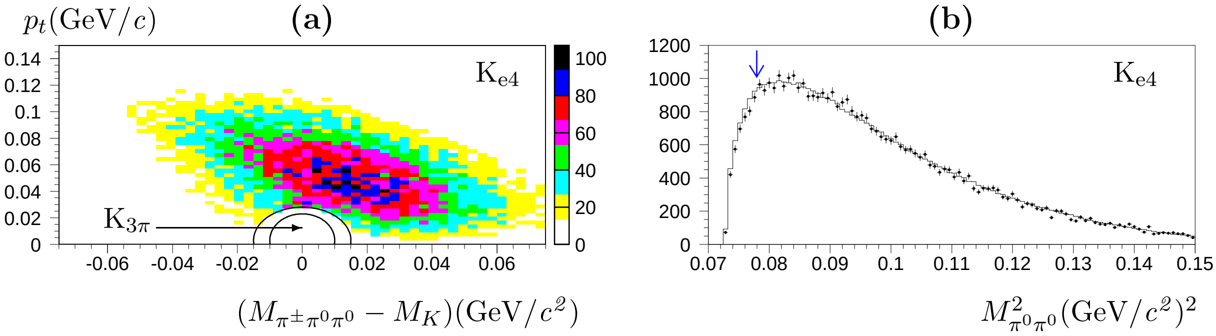

Figure 1: **(a)** Distribution of selected $\mathrm{K_{e4}}$ events in the plane $(M_{\pi^\pm\pi^0\pi^0} - M_K, p_t)$. $\mathrm{K_{3\pi}}$ normalization events (not displayed) cluster inside the tight cut contour. **(b)** Distribution of $M^2_{\pi^0\pi^0}$ for data (dots) and simulation (histogram) . The arrow indicates the $(2m_{\pi^+})^2$ threshold.

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[b] because of the light mass of the electron, about 45% of the signal events are discarded at trigger level by the anti $\mathrm{K^\pm} \to \pi^\pm\pi^0$ cut while the $\mathrm{K_{3\pi}}$ events are unaffected